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In Re U.S. Patent Application

Applicant:	Munir H. Nayfeh
Serial No.:	09/496,506
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For:	SILICON NANOPARTICLE FIELD EFFECT TRANSISTOR AND TRANSISTOR MEMORY DEVICE
Art Unit:	2811
Examiner:	Sara R. Crane

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December 29, 2004
Date

Registration No. 43,874

F-CLASS.WCM
Appr. February 20, 1998 *Attorney for Applicant*

DECLARATION OF MUNIR NAYFEH

1. I reside at 402 East Willard Street, Urbana, Illinois 61801, USA.

2. I am a citizen of the United States of America.

3. I am an inventor of the above-identified patent application.

4. I earned my Bachelor's and Master's degrees from the American University of Beirut in 1968 and 1970, respectively. I earned a Ph.D. in physics from Stanford University in 1974.

5. I served as a postdoctoral fellow and research physicist at Oak Ridge National Laboratory from 1974-1977, and as a lecturer at Yale

University in 1977, before joining the physics faculty at the University of Illinois at Urbana-Champaign in 1978, where I have been performing research and teaching to this date. My current position is Professor of Physics.

6. Relevant academic awards or achievements include: IR 100 award for single atom detection (1977); Energy 100 (1977); Beckman Award (1985); AT&T Award (1989). American Men and Women of Science; Who's Who in Science & Technology; Who's Who in Technology Today; Who's Who in Engineering; Leading consultants in Technology; Dictionary of International Biography; and Men of Achievement.

7. My fields of research include atomic, molecular, and optical physics, and laser atomic spectroscopy. I believe I was the first, with colleagues at Oak Ridge National Laboratory, to develop detection of single atoms and a resonance ionization method that demonstrated the ultimate sensitivity in analytical detection of atomic concentrations down to single atoms. The achievement was widely reported in many science and industrial magazines such as Laser Focus, in addition to the representative articles:

- Resonance electron spectroscopy detects single atoms, **Physics Today**, Search and Discovery, September 1978) p17.
- **Encyclopedia Britannica** Yearbook of Science and the future (1979)p273; McGraw-Hill Yearbook of Science and Technology (1979) p103.
- **World Book** Science Annual (1978) p32.

8. Following my arrival at the University of Illinois, I developed an active experimental program to study the multi-photon (nonlinear) dissociation

of molecules as a means to enhance dissociation selectivity and to examine the behavior of hydrogen molecules in intense laser fields resulting in molecular Coulomb explosions.

9. Recently, I have investigated the fabrication and the analysis of nanometer-scale structures by employing scanning tunneling microscopy (STM) to study hysteresis effects in the formation of matter. This work provides physical insights on the fundamental nature and interactions of solids at nanometer/atomic scales, and I believe that it has significant implications for near-term technological applications in nanoelectronics and photonics. My work included picking and imaging small clusters and single molecules. I developed a two-photon laser process combined with scanning tunneling microscopy to pick individual atoms and molecules and used it to make ultrasmall writing (writing with atoms) at room temperature. The work was covered in the New Scientist:

- The Smallest Graffiti in the World, **New Scientist**, Cover and Analysis, March 7, 1992.

10. In my opinion, the relevant arts for the above-identified application include material science and engineering, electronics, optics, optoelectronics, and chemical science and engineering.

11. The above activity gave me the opportunity to study the transition from the solid to the atomistic state in silicon, the most abundant element in nature and the backbone of the semiconductor industry. My research demonstrated the existence of "sweet spots" or magic configurations in cluster size

with enhanced chemical and structural stability. In those silicon nanoparticles, I discovered stimulated emission, laser oscillation, UV photodetection, and harmonic generation, which all are forbidden or extremely weak processes in bulk silicon. The smallest magic configuration I demonstrated is a cluster of 29 silicon atoms (about 1 nm diameter), glowing in distinct blue color under UV, such that luminescence from single particles is readily detectable. It was demonstrated that a two-photon process using femtosecond infrared excitation could also induce the blue photoluminescence. Other magic configurations found include sizes of 1.67, 2.15, and 2.9 nm glowing in distinct green, yellow and red. The characteristic emission time is a few nanoseconds, indicating that the particles may have converted from indirect to direct band gap material. Two famous particles, the 1 nm and 2.85 nm, are synonymously called the blue and red particles. Because the smallest configuration consists of only 29 silicon atoms, which can be produced in macroscopic amounts, it proved amenable to testing and accurate first principle simulations.

12. My discovery of highly fluorescent discrete configurations and stimulated emission in silicon clusters was widely reported on the Internet and recognized in scientific and technical magazines including the selected items:

- First light on silicon lasers, ***Physics World*** V14, No 1 (January 2001), page 7.
- Blue light from silicon, ***Physics World Digest***, (9 January 2001).
- Small particles could find big uses, ***Photonics Spectra***, (June 2000) page 34.
- Laser emissions induced in micron-scale silicon aggregates, ***Photonics Spectra*** (April 2002), page 42.

- Let there be light, ***Nature* 409** (22 February 2001), page 974.
- Silicon lights up imaging, ***Nature biotechnology*** V 20 (April 2002), page 351.
- Electrochemical process makes ultrasmall si nanoparticles, ***Material Research Society (MRS) Bulletin*** V 25, No 6 (June 2000), page 4.
- Discretely sized Si nanoparticles fluoresce in RGB colors, ***Material Research Society (MRS) Bulletin*** V 27, No 3 (March 2002), page 172.
- Chips at light speed, ***Business 2.0*** (May 22, 2001).
- Electrochemical process makes silicon nanoparticles, ***Journal of Material*** (May 2000), page 5.
- Nanotags, ***University Business***, (June 2000), page 57.
- Silicon nanoparticles enable microscopic lasers, ***Electronic Engineering Times***, (March 4, 2002), page 61.
- H_2O_2 key in producing ultrasmall fluorescing nanoparticles, ***Biophotonic International*** (June 2002), page 4 and page 26.

13. I have carefully reviewed the above-identified patent application, including the claims in dispute.

14. I have carefully reviewed the Office Action mailed June 29, 2004 (the "Office Action").

15. I have reviewed the cited references, U.S. Patent No. 6,407,424 to Forbes ("Forbes"), U.S. Patent No. 5,714,766 to Chen ("Chen"), and U.S. Patent No. 5,703,896 to Pankove ("Pankove").

16. I do not believe that the specifications of Forbes, Chen, or Pankove disclose or enable uniform, 1 nm spherical silicon nanoparticles.

17. The specification of Forbes teaches making particles in a size range of approximately 10 Angstroms (1 nm) to 100 Angstroms (10 nm), with a uniform distribution in particle sizes by approximate anneal conditions.

18. I believe the specification of Forbes is teaching that a range of particle sizes is provided, and not uniformly-sized particles.

19. I believe the phrase "uniform distribution in particle sizes" refers to a range or distribution of particle sizes, based on a reasonable understanding by one skilled in the art of the phrase "uniform distribution".

20. I believe that the phrase "uniform size distribution" in the context of the specification of Forbes also refers to a range of particle sizes.

21. Based on my experience in the art, I believe the methods of forming a nanocrystalline silicon film as taught in the specification of Forbes would not, at a time prior to my invention, enable formation of uniform 1 nm spherical silicon nanoparticles. Particularly, I believe that the annealing process as taught in the specification of Forbes would not provide the control over particle size needed to form uniform 1 nm silicon nanoparticles.

22. I believe the specification of Forbes does not teach to one skilled in the art how to make uniform 1 nm spherical silicon nanoparticles.

23. I believe the specification of Chen does not teach forming uniform 1 nm silicon nanoparticles.

24. I believe the specification of Chen teaches a nanocrystal 34 confined by length, width, and height equal to or less than 40 nm.

25. I believe the specification of Chen teaches a 1-2 nm thick silicon quantum dot, in Col. 4, lines 55-56, but I do not believe the specification of

Chen teaches that the other dimensions of the quantum dot are necessarily 1-2 nm as well.

26. I believe, from reviewing FIG. 1 of Chen and the quantum dot shown therein, it is very likely that the nanocrystal is significantly larger than 1-2 nm along dimensions other than thickness. For example, I believe dimensions other than the thickness are explicitly labeled in FIG. 2 (of which FIG. 1 is a cross-section) to be 20 nm and 8 nm. The nanocrystal 34 in FIGs. 1-2, I believe, has the dimensions of the control insulator layer 38, the barrier layer 30 (just above it and just below it), and the gate stack 28. I believe it basically matches the size of the active region of the device. I believe, from reviewing FIG. 8 (of which FIG. 9 is a cross-section) of Chen and the quantum dots shown therein, the dots are clearly cylindrical in shape, and it is very likely that the nanocrystal is significantly larger than 1-2 nm along dimensions other than thickness. For example, dimensions of the nanoparticle film other than the thickness are believed to be explicitly given (column 7, line 43) to be 0.4 micrometer and 20 micrometer (or 400 nm and 20,000 nm). I believe Chen further states that nanocrystals or quantum dots in one of the two-dimensional arrays may have a density of 10^{12} cm^{-2}. I believe this density corresponds to 10^{6} cm^{-1}. This, I believe, puts 40 nanoparticles along the width and 2,000 particles along the length, with the center-to-center particle interspacing being 10 nm. My estimate is that the particle size is about 5 nm. Moreover, I believe, the staircase voltage of the threshold as a function of the gate voltage was measured at liquid nitrogen temperature of - 77 centigrade, which I

believe is an indication that the device is not yet a room temperature device. In addition, I believe the staircase structure is barely resolved even at this low temperature. These observations, I believe, are consistent with nanocrystals whose width and length are comfortably larger than 1-2 nm (of the order of 5 nm).

27. I do not believe the specification of Pankove teaches uniform, 1 nm, spherical silicon nanoparticles.

28. The specification of Pankove teaches, at col. 4, line 66 to col. 5, line 8, that quantum dots 37 are in the shape of cylinders, about 15 angstroms high and about 15 angstroms in diameter.

29. The specification of Pankove also teaches that, for blue light, each dot 37 must be about 10 angstroms in diameter and depth.

30. I believe that the specification of Pankove refers only to diameter and depth, and that this is because these two dimensions are used in the art to define cylinders, also referred to as needles.

31. I believe the silicon nanoparticles of my invention are referred to in the above-identified application by diameter.

32. I believe one skilled in the art would appreciate that the use of diameter alone to define the present silicon nanoparticle's size is intended to describe its shape as being spherical; i.e., confined by 1 nm in all directions.

33. I do not believe the specification of Pankove teaches a silicon nanoparticle that is confined by a 1 nm size in all directions.

34. I believe a small cylindrical particle as described in the specification of Pankove, having a 1 nm (10 angstrom) diameter and 1 nm (10 Angstrom) depth would have a corner-to-corner dimensional length of about 1.414 nm, significantly greater than the 1 nm confinement of a spherical 1 nm diameter nanoparticle.

35. I do not believe the specification of Pankove teaches a method that, at a time prior to my invention, would enable one skilled in the art to make uniform 1 nm spherical silicon nanoparticles.

36. I believe the Office Action states that single particle tunneling has not actually been shown, and would require undue experimentation to produce.

37. I have reviewed claims 5-7, and the above-identified patent application.

38. I believe the subject matter described in claims 5-7 is described and enabled in the above-identified patent application.

39. I believe the above-identified patent application describes an experiment representing operation of a single electron device having the features described in claims 5-7.

40. I believe the background of the above-identified patent application describes a single electron device in which a semiconductor substrate is coated with a thin layer of insulating material, and the tip of a scanning tunneling microscope is positioned over it. The background describes that researchers controlled the movement of single electrons into and out of minute

blobs of indium by manipulating the voltage applied to the tip and the substrate. An example of this method, I believe, is described in a *New Scientist* article. This basic arrangement has been, I believe, interchangeably coined a single electron switch, a single-electron device, and, explicitly, a transistor (7 March, No. 1811, page 42-45 (1992)). Other researchers refer to it as analogous to a single-electron transisitor (Physics Today Jan 1993, page 24).

I believe the indium nanoparticles film in this arrangement constitutes a non-controllable gate since there is no direct electrical contact in this configuration that may be used to change/manipulate the voltage across the indium film independent of the voltage across the Source-Drain. See Exhibit A, attached hereto, which is a copy of the *New Scientist* article, and Exhibit B, which is a copy of the 1993 Physics Today article.

41. I believe a problem with the method described in the background of the above-identified patent application is its operation at relatively higher temperatures, such as room temperature, as reasonably long range quantum effects were, I believe, mostly observed near liquid helium/liquid nitrogen temperature.

42. I believe, based on my knowledge of the art, the description in the above-identified patent application, for example, page 4, line 16 to page 6, line 16, explains the applicable theory as to why a single electron device having spherical 1 nm silicon nanoparticles can operate at high temperatures.

43. I believe the above-identified patent application, for example, page 6, line 26 to page 7, line 1, describes that irradiation of the silicon nanoparticles creates and manipulates externally the necessary charge vacancies to display features for single electron operation.

44. I believe the experimental device described at page 7, line 2 to page 10, line 22 and shown in FIG. 1 of the above-identified patent application supports all of the features of claims 5-7.

45. I believe a single electron device, and operation thereof, as described in claim 5 is provided at page 7, line 2 to page 10, line 22.

46. I believe a source of the single electron device as described in claim 5 is provided as tip 12, described in page 7, lines 8-9.

47. I believe a drain as described in claim 5 is provided in substrate 16, as described in page 7, lines 8-9.

48. I believe the silicon nanoparticle film material 14 acts as a gate, as provided in claim 5. I believe the film material 14 with 1 nm silicon nanoparticles contained in the film represents the quantum well. In the exemplary configuration shown and described, there is no direct metal contact that may be used to manipulate the voltage across the film independently of the voltage across the Source-Drain. However, the use of the radiation electric field to manipulate the charge in the nanoparticle film in the configuration shown and described constitutes a non-contact manipulator, which I believe would be understood in the

art to be a means to change the electrical state of a gate, i.e., a means to control the gate for the single electron device (Please see Exhibit A).

49. I believe the experimental setup provided in the above-identified patent application would be understood by those in the art to represent a standard convenient prototype for testing features necessary for the operation of a single-electron transistor. Particularly, in the experiment shown and described, I believe silicon nanoparticles act as the gate, though a metal electrode acting as a third electrode is not provided in the experiment to change the voltage of the gate. Instead, light irradiation provides a "third electrode", as would be understood by those of ordinary skill in the art. More specifically, an on/off operation of a laser beam produces and allows the reduction of charges, respectively, in nanoparticles of the gate. The laser beam delivers an electric field, analogous to an application of a voltage in a gate having an electrode.

50. I believe this type of gate is referred to by those of ordinary skill in the art as a "floating gate", because it is controlled without contact. I believe the uniformity of the silicon nanoparticles used in a floating gate of preferred embodiments of my invention provides a sharper threshold than other floating gate designs.

51. I believe that one skilled in the art would recognize that the experimental setup shown and described in the above-identified patent application can be used to test the effects of single-electron operation for a single-electron device including a gate, as well as a transistor having a gate.

52. I believe hole creation as described in claim 5 is provided regarding the present single electron device, for example, at page 8, lines 11-14, and page 9, lines 10-15. I believe the theory behind the hole creation at room temperature as implemented by the single electron device is also described on page 4, line 16 to page 6, line 6, as stated previously.

53. I believe applying a voltage across the drain and the source as described in claim 5 is provided at, for example, page 7, lines 15-26, in which voltage is varied between the tip and the substrate. I believe that FIGs. 2 and 4 show I-V spectra for the described experiment, while FIGs. 3 and 5 show derivatives of the relationships shown in FIGs. 2 and 4, respectively.

54. I believe the feature of using light having spectral width between 300 nm and 600 nm to manipulate the nanoparticle gate by creating the hole in the silicon nanoparticles of the single electron device as described in claim 7 is provided at least at page 8, line 17 of the above-identified application.

55. I declare solemnly that all statements made herein of my own knowledge are true and all statements made on information and belief are believed to be true; and further that these statements were made with knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Dec. 28, 2004

Munir Nayfeh

Munir Nayfeh